

10/088284
JC10 Rec'd PCT/PTO 13 MAR 2002

Express Mail No. EV049901141US

PATENT APPLICATION OF
JEAN-FRANCOIS HELARD
ENTITLED

METHOD FOR EQUALISATION IN RECEIVERS
USING A COMBINATION OF MODULATION
TECHNIQUES WITH MULTIPLE CARRIERS AND
WITH MULTIPLE ACCESS BY CODE DIVISION

Docket No. F40.12-0004

10/088284

JC10 Rec'd PCT/PTO 13 MAR 2002

2/PRTS

METHOD FOR EQUALISATION IN RECEIVERS USING A
COMBINATION OF MODULATION TECHNIQUES WITH MULTIPLE
CARRIERS AND WITH MULTIPLE ACCESS BY CODE DIVISION

Field of the invention

The field of the invention is that of transmission, and more precisely reception, of multi-carrier digital signals. The invention particularly concerns the equalisation, or detection, in receivers of signals relying on a combination of modulation techniques with multiple carriers and with multiple access by code division.

The development and adjustment of techniques making it possible to transfer multimedia data simultaneously at a high transfer rate for a large number of users is primordial for future generations of Hertzian communications, making it possible continually to satisfy better the constraints of spectral efficiency linked to the penury of the spectrum and to the growing number of users.

One known approach consists of searching for an optimum combination of modulation techniques for multiple carriers with high spectral efficiency (of the OFDM type) and the techniques of Code Division Multiple Access (CDMA type). These new techniques can for example be applied to mobile telecommunications systems (of the UMTS type and UMTS

station) or to communications systems inside and outside buildings to increase the reliability and capacity of transmission.

5 State of the art

2.1 Scientific context

Since 1993, several contributions proposing a combination of modulation techniques for multiple carriers and spectrum spread have been published by several international teams [S. Hara, R. Prasad, "Overview of multicarrier CDMA" (IEEE Communications Magazine, December 1997, pp 126-166)]. Thus three families of transmission systems are known at present combining the OFDM and CDMA techniques:

- the CDMA basic multicarriers MC-CDMA (Multi-Carrier CDMA),
- the CDMA multi-pilots or MT-CDMA (Multi-Tone CDMA) and
- 20 - the CDMA direct sequence multicarriers or MC-DS-CDMA (Multi-Carrier Direct-Sequence CDMA).

They are distinctive according to the way in which they combine OFDM and CDMA functions, through their spread technique or multiple access and by their frequency division.

25 The present invention relates in particular, but not exclusively, to the first of these families; CDMA multicarrier or MC-CDMA.

2.2 Description of an MC-CDMA system

30 In the MC-CDMA modulator shown in figure 1, and already known in prior art, the data flux is above all spread over the frequency field by using a spread code, and then transmitted on the different sub-carriers of the OFDM multiplex. A fraction of each data of origin, corresponding to a

"chip" of the spread code of length L_c is thus transmitted by each of the sub-carriers N_p .

5 Thus each symbol x^n_j assigned to the user j (with $j=1\dots N_u$) and transmitted during the interval n , is multiplied by its specific spread code $C_j = [c_j^1, c_j^2, \dots, c_j^{L_c}]^T$ of length L_c where $[]^T$ signifies a transposed vector.

10 The symbols vector transmitted during the n^{th} MC-CDMA symbol by all the users can be written $X^n = [x^n_1, x^n_2, \dots, x^n_j, \dots, x^n_{L_c}]^T$ with $x^n_j = 0$ when the user j is inactive. The matrix of the codes C is then equal to:

$$C = \begin{bmatrix} c_1^1 & c_2^1 & \dots & c_{L_c}^1 \\ c_1^2 & c_2^2 & \dots & c_{L_c}^2 \\ \dots & \dots & \dots & \dots \\ c_1^{L_c} & c_2^{L_c} & \dots & c_{L_c}^{L_c} \end{bmatrix} \quad (1)$$

15 where the j^{th} column vector of C corresponds to the spread code C_j of the user j .

20 In the case of a downstream connection where the different signals addressed to the different users are emitted in a synchronous way, the codes used are generally chosen to be orthogonal, which makes it possible to obtain, in reception, better rejection of interference between users.

25 Thus, with Walsh-Hadamard codes, the maximum number of users is equal to the number of chips per code. In general, the number L_c of chips of the spread code is chosen to be equal to the number N_p of sub-carriers but variants are possible for better dimensioning of the generated signal relative to the transmission conditions (channel, cellular aspect etc.).

2.3 Detection techniques

30

2.3.1 "Traditional" techniques for linear equalisation

In an MC-CDMA receiver, the de-spreading is carried out in the frequency domain after operation of the Direct Fourier Transform implemented in the OFDM de-modulator as shown in figure 1.

5 The usage of orthogonal codes, such as the Walsh-Hadamard codes in the case of a synchronous system, guarantees the absence of multiple access interference in a Gaussian channel.

10 On the other hand, during transmission in a frequency selective channel, the orthogonality between the codes is destroyed which thus creates interference between users.

15 In the hypothesis that the length of the guard interval is longer than the spread of the impulsion response of the channel, and that the latter varies slowly relative to the length of the symbol, the channel effect on the k^{th} sub-carrier can be approximated over the whole symbol length by a complex component called $h_k = \rho_k e^{i\theta_k}$.

In this case, the channel matrix is diagonal and equal to:

$$20 \quad H = \begin{bmatrix} h_1 & \dots & 0 & 0 \\ \dots & h_2 & \dots & 0 \\ 0 & \dots & \dots & \dots \\ 0 & 0 & \dots & h_{N_p} \end{bmatrix} \quad (2)$$

By naming $N = [n_1, n_2, \dots, n_{N_p}]^T$ the vector representing the noise terms and n_k the noise term affecting the k^{th} sub-carrier $\tilde{n}_N^2 = E/|n_g|^2$, $k = 1, \dots, N_p$, the vector obtained is then:

$$25 \quad R = [r_1, r_2, \dots, r_{N_p}]^T = H.C.X + N \quad (3)$$

The matrix G of dimension $N_p \times N_p$ is the matrix for equalisation coefficients.

30 The mono-user detection techniques consist of detecting the useful signal without taking into account interference between users. After operation of the Direct Fourier

Transform, the signal received is equalised in the frequency domain by multiplying each symbol received by a coefficient g_k belonging to each sub-carrier, with the aim of compensating the attenuation \tilde{n}_k and the de-phasing \tilde{e}_k introduced by the 5 channel at the frequency under consideration.

The different detection methods are the following (non-limiting list):

10 • "Maximum Ratio Combining" (MRC): the MRC method is optimum relative to the error level in the case where a single user is active. It consists of multiplying each symbol by the conjugated complex response of the channel:

$$g_k = h_k^* \quad (4)$$

15 • "Equal Gain Combining" (EGC): the EGC detection technique only corrects the phase distortion of the channel:

$$g_k = h_k^* / |h_k| \quad (5)$$

20 • "Orthogonality Restoring Combining" (ORC) or "Zero Forcing" (ZF): the ORC technique makes it possible to eliminate integrally the interference between users by restoring orthogonality between the different spread codes. In this case, the coefficients are equal to:

25

$$g_k = 1/h_k \quad (6)$$

However, the main disadvantage of this method is that, for low amplitudes h_k , the multiplication by an inverse function of the channel results in high amplification of noise, which rapidly degrades the error level.

30 • "Controlled equalisation" (CE) or "Threshold ORC" (TORC): the CE technique consists of multiplying the signal received by the inverse function of the channel only when the 35 module $|h_k|$ of the frequency response of the channel for the

carrier concerned exceeds a certain threshold. An improvement of this procedure can be obtained by applying the EGC for the carriers which have been greatly attenuated, which makes it possible to compensate for the distortion of 5 the channel phase for the sub-carriers under consideration.

2.3.2 The classic detection technique according to the criterion of the "Minimum Mean Square Error" or MMSE.

10 The equalisation traditionally proposed in MC-CDMA according to the MMSE criterion is aimed at minimising independently, on each carrier k the mean square error value ε_k between the signal transmitted s_k and its estimate $s=g_k r_k$ generated at the output from the equaliser:

$$15 \quad J = E \left\{ |\varepsilon_k|^2 \right\} = E \left\{ |s_k - g_k r_k|^2 \right\} \quad (7)$$

When the number of users is equal to the length L_c of the code, the coefficients of the equaliser according to the criterion of minimum mean square error are equal to:

$$20 \quad g_k = \frac{h_k^*}{|h_k|^2 + 1/\gamma_k} \quad (8)$$

where γ_k is the signal to noise ratio for the sub-carrier k . When the number of users N_u is lower than the length L_c of the code, the equaliser coefficients according to the minimum mean square error criterion are equal to:

$$25 \quad g_k = \frac{h_k^*}{|h_k|^2 + \frac{L_c}{N_u} \frac{1}{\gamma_x}} \quad (9)$$

30 where γ_x is the signal to noise ratio of the transmitted signal x .

This is described in particular in the document by S. Kaiser, "Analytical performance evaluation of OFDM-CDMA

mobile radio systems" (Proceedings First European Personal and Mobile Communications Conference (EPMCC'95), Bologna, Italy, November 1995, pp 215-220).

5 In the same way as for the other detection techniques, the equalisation function is thus carried out on each sub-carrier independently by multiplying, in the frequency domain, each of the N_p symbols generated at the output from the FFT by a single coefficient g_k belonging to each sub-carrier.

10 Aim of the invention

The particular aim of the invention is to propose a new technique for equalisation, or for detection, which is more efficient than the techniques known from prior art described above in MC-CDMA, in particular when the system is not 15 operating at full load, that is to say when the number of users is less than the length L_c of the spread code.

Description of the invention

This aim, together with others which appear more clearly 20 below, is achieved with the help of a method for reception of a signal implementing a modulation with multiple carriers and with multiple access through code division, of the type comprising a stage of demodulation by application of a mathematical transform from the temporal domain to the 25 frequency domain, a stage of equalisation (or detection) of the transformed signal, and a stage of de-spreading of the treated signal.

According to the invention, said equalisation stage takes 30 into account, for each of the components of said transformed signal, the disturbances affecting the carrier carrying said component and at least one other of said carriers and at least some of said spread codes.

Thus, equalisation is carried out according to an approach different from prior art techniques, which rely 35 simply on the application of a multiplication coefficient on

each component. According to the invention, the disturbances of the transmission channel are taken into account as a whole, or at least the disturbances due to some of these carriers. It is verified that this technique makes it possible to obtain better 5 results, particularly when the system is not operating at full load.

Thus, the invention concerns a technique for equalisation, which minimises the mean square error for the received signal as a whole, by integrating the de-spreading 10 functions into it. This approach thus requires taking into account the different spread codes of the active users.

Advantageously, said equalisation stage implements an equalisation matrix containing the equalisation coefficients of the transmission channel, at least some of the coefficients 15 other than the coefficients of the diagonal of the matrix sometimes being non nil.

It is therefore simple to put the technique according to the invention into operation, in the receivers.

Advantageously, the coefficients of said weighting matrix 20 are determined according to the Wiener filtering technique applied globally over the whole of the signal received, taking into account the de-spreading functions.

This weighting matrix can thus be written:

$$25 \quad G = H^* \left(H.C.A.C^T.H^* + \frac{\sigma_N^2}{E_s} I \right)^{-1} \quad (14)$$

with: H = matrix representative of the transmission channel;

C = matrix of the spread codes;

30 $A = \{a_{jj}\}$: diagonal matrix with a_{jj} non nil if the user j is active;

σ_N^2 = noise variance affecting each sub-carrier;

$E_s = \{x_j^2\}$: power of received signals;

I = the identity matrix.

When σ^2_N/E_s tends towards 0, it may happen that this matrix is not reversible. In order to overcome this problem, one can envisage that the estimated quantity σ^2_N/E_s may be compared to a threshold value, and replaced by said threshold value when it is lower than the latter.

Advantageously, one can also envisage that, when the estimated quantity σ^2_N/E_s is lower than a threshold value, one implements an alternative detection technique, such as the so-called ORC technique.

Another advantageous solution to this problem consists of determining said weighting matrix with the aid of an iterative procedure implementing a gradient algorithm.

When the reception process implements a non-linear multi-user detection technique of the parallel and/or series annulment type, (the different spread codes for multiple users being known by the receiver), the same equalisation technique is used advantageously in a stage for annulment of multiple access interference, due to other users.

In this case, the said annulment stage can be iterative, and comprise at least two successive equalisation steps.

The method according to the invention can thus comprise the following stages:

- an initial stage producing an estimate of multi-user interference;
- 25 - a subtraction stage of said estimate of multi-user interference from the received signal;
- an equalisation stage on the corrected signal thus obtained.

The invention also concerns the equalisation method implemented in the reception process described above, together with provisions for reception applying these procedures.

5 List of Figures

Other characteristics and advantages of the invention will be seen more clearly by reading the description below of a preferred embodiment of the invention, given as a simple illustrative and non-limiting example, and the attached 5 drawings among which:

- figure 1 shows a general overview diagram of an MC-CDMA transmission and reception channel, of known type;
- figure 2 shows a general overview diagram of an MC-CDMA transmission and reception channel according to the 10 invention;
- figure 3 is a comparison of the performance of different techniques for linear detection;
- figure 4 shows a general overview diagram of an MC-CDMA non-linear multi-user receiver with annulment of 15 parallel interference.

6. Description of a preferred embodiment

6.1 The new detection technique proposed (matrix MMSE)

20 This new detection technique thus has the aim of minimising the mean square error globally over the received signal as a whole. If one calls $W_j = [w_j^0, w_j^1, \dots, w_j^{N_p}]$ the optimum weighting vector, the symbol given to the j^{th} user can be written:

25

$$\hat{x}_j = W_j^T \cdot R = C_j^T \cdot G \cdot R \quad (10)$$

It can thus be noted that one takes into account de-spreading functions during this operation of minimisation of 30 the mean square error.

According to Wiener filtering, applied to the received signal as a whole, the optimum weighting vector is equal to:

$$W_j = \Gamma_{R,R}^{-1} \cdot \Gamma_{R,x_j} \quad (11)$$

where $\Gamma_{R,R}$ is the autocorrelation matrix of the vector R received and Γ_{R,x_j} is the intercorrelation vector between the symbol x_j and the vector of the received signal R . These quantities are equal to:

5

$$\begin{aligned}\Gamma_{R,R} &= E\{R^*R\} = H^*C E\{X^*X^T\}C^T H + E\{N^*N^T\} \\ \Gamma_{R,x_j} &= E\{R^*x_j\} = H^*C E\{X^*x_j\}\end{aligned}\quad (12)$$

where $(\cdot)^*$ means conjugated complex. The optimum 10 weighting vector is then equal to:

$$W_j^T = E\{x_j X^*T\} C^T H^* (H^* C E\{X X^*T\} C^T H^* + E\{N N^*T\})^{-1} \quad (13)$$

If the different noises affecting the sub-carriers have the 15 same variance and are independent, then $E\{N N^*T\} = \sigma_N^2 I$ where I is the identity matrix. If the different user signals have the same power ($E\{x_j^2\} = E_s$ and are independent, one can write that $E\{X X^*T\} = E_s A$, here $A = (a_{ij})$ is a diagonal matrix with $a_{jj}=1$ if the user j is active and $a_{jj}=0$ if the user j is inactive. The matrix for 20 the equalisation coefficients is then equal to:

$$G = H^* \left(H^* C A C^T H^* + \frac{\sigma_N^2}{E_s} I \right)^{-1} \quad (14)$$

Evidently, the conditions described in the preceding 25 paragraph for the variance and independence of noise affecting the different sub-carriers on the one hand and for the power of the signals are completely unnecessary for validating the approach.

In the case of full load ($N_u = L_c$), and when orthogonal 30 codes are used such as Walsh-Hadamard codes, the quantity $C A C^T$ is equal to the identity matrix and the matrix G of the equalisation coefficients is then a diagonal matrix with the equalisation coefficient of the k^{th} sub-carrier equal to the

expression (8) given above. It must be noted that, in the given example, the reception powers are the same for all users.

On the other hand, in all the cases where $N_u < L_c$ the quantity $C.A.C^T$ is not an identity matrix and the G matrix for the 5 equalisation coefficients is not a diagonal matrix. The receiver proposed then complies with the diagram of figure 2.

If the reception power of the signals from different users is not the same for all users, the new approach remains optimum relative to the MMSE criterion. In this case the 10 calculation leads to a matrix A , still diagonal if all the users are independent, but for an active user j , a_{jj} can be different from 1.

Contrary to the approach according to the invention, prior art technique according to the MMSE criterion leads to a 15 non-optimum equation (8) in cases where operation is not at full load, and even in the case of full load, this approach is not optimum relative to the MMSE criterion if the power of the different users is not identical.

The matrix G is a dimensional matrix $N_p \times N_p$. The method 20 proposed thus consists not of multiplying each symbol generated at output from the FFT by a coefficient accorded to each sub-carrier, but of treating the signal vector R as a whole in conformity with the preceding calculation by multiplying it by the matrix G .

25 This new detection technique requires knowledge of the different spread codes of the multi-users, and accordingly, it can be classified among the linear type multi-user detection techniques.

30 Direct application of the equation (14) requires inverting the matrix corresponding to the denominator of this equation. In certain cases, in particular when the quantity σ_N^2/E_s tends to zero, which is verified when the signal to noise ratio is very high, the matrix as expressed by the equation (14) may not be reversible.

A first possibility for overcoming this disadvantage consists of using a threshold device in such a way that the estimated quantity σ_N^2/E_S is limited and thus equal at least to a value optimised by taking into account the precise parameters 5 of the system under consideration. In this case, the matrix is always reversible.

A second possibility for overcoming this disadvantage consists of using, when the estimated quantity σ_N^2/E_S tends to zero, another detection technique such as, for example, the Orthogonality 10 Restoring Combining method (ORC) described in paragraph 2.3.1.

Moreover, an alternative to the matrix inversion for implementing the proposed detection technique, called matrix MMSE, is to use an iterative process, relying on a gradient 15 algorithm such as Last Mean Square (LMS), for example. In this case, the minimisation of the mean square error according to Wiener filtering, makes it possible to obtain optimum coefficients, after several iterations, for the equalisation matrix G given by equation (14).

20

6.2 Application to non-linear detection techniques with interference annulment

There are three main categories of multi-user detectors: Maximum Likelihood Detectors (MLD), linear detectors such as 25 the detector described above, and non-linear detectors with interference annulment. In this paragraph, particular attention is given to this third category. Detectors with interference annulment of parallel type such as shown in figure 4, as well as the detectors with interference annulment of the series type 30 seek to estimate the interference due to other signals in order to delete this multi-user interference from the received signal. This procedure can be implemented in an iterative way, with the aid of several successive detection stages. Different mono-user detection techniques can thus be combined at different 35 stages. The new method proposed for implementing the MMSE

detection algorithm can also be chosen at each stage of a multi-user detector with interference annulment. In this case, the matrix A of the equation (14) must be optimised in a specific way at each step. Thus it becomes possible to combine 5 linear and non-linear multi-user detectors.

As an example, figure 4 shows a diagram of the principle of a detector with interference annulment of the parallel type with two steps implementing the new detection technique proposed. In the initial step, the symbols of the K_u-1 other 10 active users are detected in parallel by implementing the new matrix MMSE algorithm (equalisation matrix G1). Thus, it is possible, after de-spreading, through de-mapping (SBC⁻¹), decision taking, mapping, (SBC - Signal Binary Code), the spread and multiplication by the matrix H of the channel 15 coefficients to obtain an estimate of the multi-user interference which is then subtracted from the received signal. The second step next carries out the final detection by using once again the new matrix MMSE algorithm (equalisation matrix G2).

20

6.3 Examples of results

The results presented are obtained with independent Rayleigh procedures and with the same power for each sub-carrier, the channel being considered frequency non-selective 25 on each of these sub-carriers. The Gaussian additive white noise is also generated by procedures of the same power and independent for each sub-carrier. The codes used are Walsh-Hadamard and the signal binary coding is that of an MDP4.

Figure 3 shows the performance of different mono-user 30 detection techniques with $L_c=N_p=64$ taking into account the spectral efficiency of the ratio E_0/N_0 needed to obtain a $BER=10^{-3}$. The maximum spectral efficiency is equal to 2bit/s/Hz corresponding to a full load system ($N_u=L_c=N_p$), since the losses due to the guard time, the synchronisation and

channel estimation (pilot carriers for example) are not taken into account.

Curve (b) shows the performance of the traditional MMSE system with equalisation coefficients optimised 5 independently on each sub-carrier in conformity with the equation (9) with one coefficient per sub-carrier. Curve (a) corresponds to the performance of the new MMSE system using the matrix approach with equalisation matrix coefficients given by the equation (14). At full load ($N_u=64$) 10 the performance of the two MMSE systems are identical. On the other hand, when the system is not fully loaded ($N_u<64$), the new matrix MMSE system provides a gain of about 2 dB for $N_u=32$ and 16, which corresponds to a spectral efficiency equal respectively to 1 and 0.5 bit/s/Hz.